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THERMAL STRESSES IN CONTINUOUS DC CASTING OF AL ALLOYS

DISCUSSION OF HOT TEARING MECHANISMS

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Thermal stresses are computed by a finite differences method with an elasto-plastic model. Properties of cast alloy are represented by a schematic strain-stress curve at every temperature.

Data include properties of metal measured at different temperatures and experimental or computed distribution of temperatures. Surface residual stresses measured by X Rays methods on small cast billet and quenched cylinders were in good agreement with the model.

Computed results for D.C. cast round billets are presented as a function of size and casting speed. Either these values or influence of coarsening of internal structures on mechanical properties cannot explain increasing hot tearing tendancy with the size of the billet.

It is shown that hot tearing could occur as a consequence of propagation of cracks, under stresses slightly above yield stress, from defects as intergranular decohesions or microshrinkage induced above the solidus temperature before complete solidification. Parameters influencing the formation of such defects are reviewed.

Introduction

Metallurgists call for cast products of increasing size in the most hard alloys, while claiming constant structural quality.

Good structures can only arise from the highest cooling rates. In continuous D.C. casting, this involves that the skin is strongly water cooled and therefore strengthened before the freezing of the heart is complete. The further cooling of internal parts finally results in internal tensile stresses associated with compressive stresses in the skin.

These stresses are sometimes strong enough to initiate cracking during casting but anyhow they generally induce plastic strain in some parts of the casting so that after complete cooling residual stresses are still present.

We shall consider only the case of round billets and in a first part try to estimate thermal stresses in the steady state. The stresses induced during the transient start of the casting operation are also an important problem, but they are too much difficult to calculate. It is known that even if the start is well controlled, in many cases for the biggest billets cracks or tears continue to form throughout the whole casting.

In a second part, the results of the calculations corresponding to different real casting processes will be presented.

We shall then discuss, from preceding speculative considerations and new experimental results the possible mechanisms of hot tearing.

Model for thermal stresses calculation

Finite differences method

The cylindrical billet moves downward in a stationary field of temperatures. It is slit in finite elements, as shown in figure 1, by a system of horizontal planes, cones and cylinders.

We consider a finite cylinder, with a height H, as a stack of n slices. It progresses from an initial completely liquid state to a solid state with a mean temperature of about 50°C (figure 2). We assume that upper and lower surfaces of this cylinder are free and we consider the stresses resulting from its thermal history in the central slice of the stack, after sucessive increments of time Dt such that the thickness of an elementary slice divided by Dt equals the casting speed.

This simplification consists to neglect the influence of vertical long distance effects on final stresses. The number of slices is limited by the time of computer calculation.

Physical basis of the model.

In the elastic field, stresses are classicaly related with strain by Hooke's laws.

In the plastic field, increments of strain are calculated from Prandtl-Reuss' relations, according to the derivation introduced by Yamada (1). The elastic-plastic boundary is tested by the Von Mises' criterium which compares an equivalent stress including all elementary stresses to the yield stress (after consolidation in the case of prior plastic strain).

In the case of variable temperature, total strain includes thermal expansion.

From geometrical considerations, the strains in the center of each element can be related with the displacements of the nodes of the network.

We consider the forces which, applied at the nodes of the elements, would produce the real strains. These forces can be expressed as a function of displacements of the nodes, by using the theorem of virtual works. They are resolved in two contributions, one of them being directly related to the increment of temperature.

Finally, the steps of calculations are as follows : from a known strain-stress situation, an increment of temperature is introduced in each element, corresponding to the temperatures after the increment of time Dt. Then, equating the forces at all the nodes throughout the cylinder, we get a system of equations from which the unknown incremental displacements can be calculated. From other equations, incremental strains and stresses are then computed. The new total strains and stresses are used in the next step of calculations.

An iterative process is applied if the cumulated stress leads to a change from elastic to plastic state or reciprocally.

More details on this model are given in reference (2).

Mechanical properties of cast alloy

Mechanical properties of cast alloy are to be known at every temperatures.

In the model the strain-stress curves are schematized as shown on figure 3 : the consolidation of material is represented by a linear function, the slope being used as a kind of modulus of plastic deformation (1).

This simplification surely produces some distorsion from true values. However, experience shows us that if we caracterize the level of stresses by parameters as ratio of maximum stress over yield stress or cumulative plastic deformation, rather than by absolute value of stress, the model is helpfull to study the influence of casting parameters and resulting temperatures fields.

Yield stress, Young's modulus E and modulus of plastic deformation E' were experimentally measured from tensile test on samples machined in as cast 2014 and 7075 billets. For high temperature measurements, a special device was used to heat the sample as quickly as possible in order to preserve cast segregated structure. At low temperatures, Young's modulus was also determined by a classical method of ultrasonic resonance.

Our values (figure 4) are in good agreement with published values (3) for 2014 alloy. Above solidus temperature we assume complete incoherency as in liquid.

Comparison of residual surface stresses with experiment

We have at our's disposal a method for measurement of residual stresses at the surface of a solid by X Rays (4).

We tested our model first on quenched cylinders. Calculations were done with the same basic model adapted for quenching description. The cylinders were quenched from 500° C, in cold and boiling water, and with a coating. The temperatures were experimentally determined by another laboratory (5), and the mechanical properties were here measured with convenient heat tratment.

Table I. Surface residual stress on quenched cylinders (ksi)

Sample	Calculated stress	Measured stress
14 quenched in water 20°C	28	30
14 quenched in boiling water	14	16
14 quenched in boiling water after coating	3.1	3.6

The agreement appears satisfying considering the assumptions done in the model.

We could also test the model for casting in the case of a 2014 billet of 5 inches diameter cast with a speed of 5 inches/mn. The stress measured by X Rays on a part of 8 inches long sawed in the billet was 14 ksi, while calculated value was 12.5 ksi.

Discussion of results

The temperature distributions used for calculations were experimentally established from records of fine themocouples introduced on the top of the billets in the liquid sump and moving down inside it. In some cases we used computed temperatures from a model which gives temperatures inside a billet if we know the temperature of the surface of the lateral skin. That temperature is then recorded from a very fine thermocouple introduced less than 1/20 inch under the surface.

Figure 5 shows the temperatures and computed stresses in a 2014 billet of 10 inches diameter.

Let us consider the successive distributions of stresses in horizontal slices from the top to the bottom of the billet.

About the bottom of the mould, the skin is submitted to important tensile stresses leading to plastic deformation. This is due to high cooling rate at the surface, the situation is quite similar to a quench of the freezed ring.

The subsequent cooling of layers of metal soon causes an inversion of the sign of stresses : the skin becomes compressed while the hotter internal layer is in extension.

When the freezing of the heart is achieved, the compressive surface stresses grow again and reach the yield stress producing increasing amount of plastic strain of a strong, almost completely cooled surface layer. At the opposite, in the center, tensile stresses increase slowly, but the metal is yet more ductile. The yield stress is reached at about 400° C as a consequence of strengthening of material with cooling.

Stresses and plastic strain continue to progress slightly until the heart reaches the same temperature than the skin.

Influence of casting parameters

Casting speed. The figure 6 shows the influence of casting speed on calculated internal stresses in the center of 10 inches 2014 billet with a mould of 4 inches height. This shows that increasing speed will surely lead to the fracture of the metal when reaching the limit of resistance, in steady state conditions even if special starting conditions allow to begin without cracking.

Secondary water cooling. The secondary direct cooling by water has but rather little importance. More precisely neither water flow nor water temperature, in customary limits influence decisively the level of stresses : the simple reason is that the remperature of the skin is allways under approximately 150° C at the contact with water and decreases to 80-100° C rather quickly. Inside these limits the strenght of the skin is nearly constant and the cooling rate in the heart is hardly affected.

Influence of mould. The height of the mould, its composition (copper, aluminium), its conicity, the efficiency of its cooling affect the final residual stresses, as they affect the cooling rate at the surface, but calculations show that this remains a minor effect.

Size of billet. Stresses distributions were computed for billets of respectively 4, 6, 10, 20 inches diameter, using experimental temperature fields, each billet being cast with the usual casting speed. The tensile stresses at the center lye beetween 8.5 and 9.4 hbar, values not significantly different.

This must not be surprising if we notice that customary casting speed, as reported by many authors, appears to be proportional to the reciprocal of diameter. If we remember that, as a first approximation the depth of the sump or of any isotherm is proportional to the casting speed and to the squared diameter, as a consequence, in practice, there is a proportionality between diameter and depth of isotherm that is to say an homothesis between temperature distributions.

From this homothesis, it is obvious that the resulting thermal stresses will be the same.

Then, what is surprising is that with normal casting speed, people meet with more difficulties of cracking for large billets.

The cracking tendency of large billets, while normal level of stresses, could be explained by a modification of mechanical properties, the structure becoming coarser.

In order to test this assumption, we compared strain-stress curves drawn from samples machined in cast material presenting various dendritic sizes(from 50 to 100 microns), and various amounts of porosity and inclusion (well degassed and untreated metal). The properties measured at 400, 200° C and room temperature were not significatively different with the structure.

As a conclusion of these observations, it seems that neither the level of stresses, nor the properties of cast metal can explain greater tendancy of large billets to tear.

Hot tearing mechanisms

Experimental observations on 20 inches 7075 billets

A first series of 7075 billets of 20 inches diameter was cast with a mould of 4 or 5 inches height and a casting speed from 1 inch 1/4 to 1 inch 1/2 per minute. Different starting techniques were used as aluminium bottom or progressive start to eliminate the influence of initial transient stage. In all cases, various kinds of cracks formed inside billets throughout the whole lenght.

Stresses in the center were computed using experimental isotherms and mechanical properties measured at different temperatures on the same alloy : tensile stress was estimated between 8 and 9 hbar, higher than measured yield stress but allways lessthan fracture stress measured on samples.

The billets were then successfully cast by two methods.

In the first one, a mould very high was used with a low water flow and a very slow speed. With special device for starting many billets were cast without cracking. The tensile stresses computed from experimental isotherms were slightly under the yield stress in the center.

In the second one, we used the normal mould but water was completely spread out at a distance under the mould by air wipers which produce a reheating of the skin. This technic combined with an original starting method gave excellent results. Computed stresses were found again under the yield stress in the center.

In a seriesof billets cast with the second method we systematically examined by various metallographic methods the structure of slices sawed in billets. For well treated metal, with low concentrations in sodium and hydrogen or inclusions, structure was perfectly sound, without porosity.

In billets cast from bad melts containing too much sodium or not correctly degassed, we noticed in addition to porosity due to hydrogen and/or inclusions defects appearing as microcracks or intergranular decohesions, or strings of microshrinkage cavities. Such a defect is shown on figure 7.

If the quality of the melt was still worse, a number of cracks of a few 1/10 inches lenght appeared and sometimes diametral cracks of 2 or 4 inches began to form. An examination of the surface of such cracks with scanning electron microscope shows (figure 8) the same appearance than inside of porosities or microshrinkage.

Mechanisms of hot tearing

From these observations it can be stated that such defects arise before complete solidification, above the solidus temperature, in the bottom of the mushy zone.

It seems probable that, according to fracture mechanics, when microcracks are thus present, cracks can develop by propagation from them with stresses under fracture stress but probably near yield stress.

Such a mechanism could explain our two results :

- we observe cracks in castings while maximum calculated stresses are less than fracture stress of cast metal
- if we are able to strongly decrease the level of stresses we cans observe microcracks inside metal.

Formation of microcracks

The cause of the defects described is the fact that, on the contrary of our assumption of complete absence of coherency above the solidus temperature, the alloy presents already some mechanical resistance (6) between coherency temperature slightly under liquidus and the solidus temperature.

The first parameter, for a given alloy is the width of the mushy zone. The microcracks may arise from both effects of microshrinkage tendency, which is directly proportional to the width of mushy zone and strenghening of partly freezed alloy.

We can then explain the effect of casting speed and of size on hot tearing only by the influence of these parameters on mushy zone.

From general litterature we can list now the parameters affecting the occurence of these defects.

-Grain size.Correlations between grain diameter and lenght of cracks formed in laboratory experiments of solidification under stresses were published.

-Presence of elements having a strong effect on interfacial energies(sodium,beryllium..).

-Gas content, inclusions. Hydrogen contributes to microshrinkage and inclusions such as oxide films behave as nuclei for precipitation of hydrogen bubbles in two dimensional cavities.

-Composition of alloy. The basic parameters are the amount of eutectic phase and the value, at the end of solidification, of the derivative *df/dT* of the percent of solid as a function of temperature.

-Relation between shear strength of the partly freezed alloy in the mushy zone and the percent of solid.

Although the influence of these factors is qualitatively known in many cases a quantitative correlation is not yet established.

Conclusions

A model based on simplified but realistic elastic-plastic desription of the behaviour of cast metal enables us to estimate, from experimental temperatures distribution, the thermal stresses and amount of plastic strain in cast billets.

The results of calculations indicate that, for a given alloy, the casting speed is the main parameter, the mould and water cooling remaining more secondary. Surprisingly, the size of billet has but little effect if the billet is cast at customary speed. This result could be rather simply demonstrated.

The heart of a billet is submitted to tension stresses generally above the yield stress but less than the fracture stress measured on cast material.

In billets cast with special device to strongly decrease the level of stresses, microcracks were observed in some cases according to metal quality. Metallographic examinations suggest that such defects are formed in the mushy zone above the solidus temperature.

It is proposed that hot tearing results of propagation under low stresses of these microcracks.

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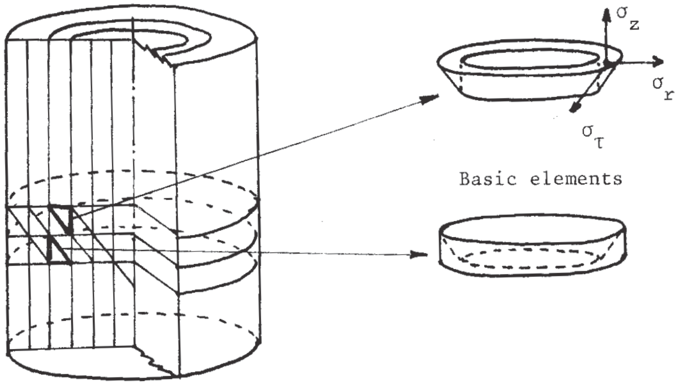
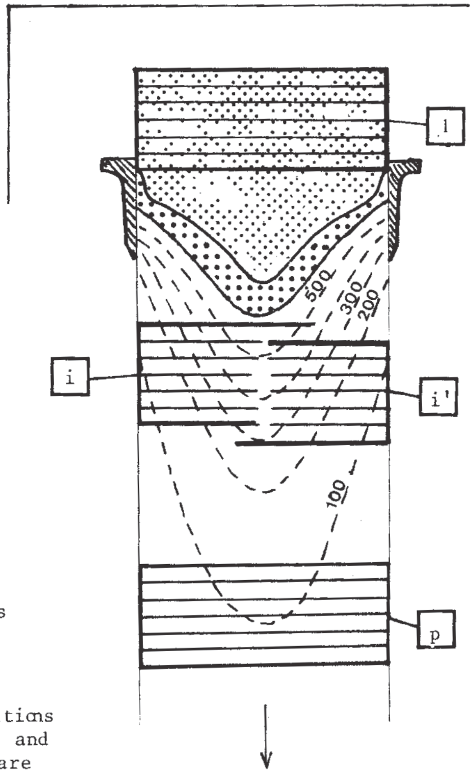


Figure 1.Decomposition of the billet in finite elements.



1. Time t=0 liquid

i . Time t

i'. Time t+dt

p . End of calculations

Figure 2.Successive positions of the stack of n slices.Upper and lower surfaces of that volume are supposed free.

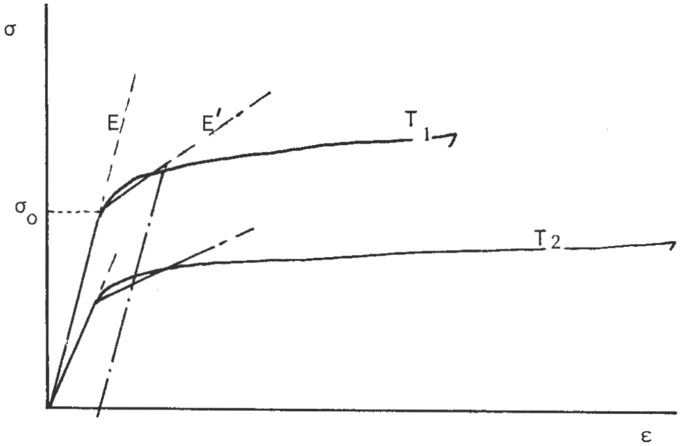


Figure 3. Schematical representation of strain-stress curves

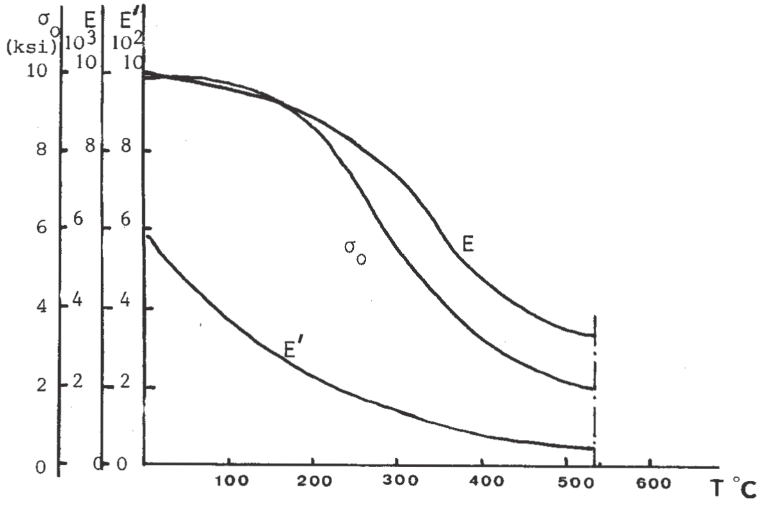


Figure 4 Yield stress,Young's modulus,modulus of plasticity versus temperature.2014 alloy,as cast.

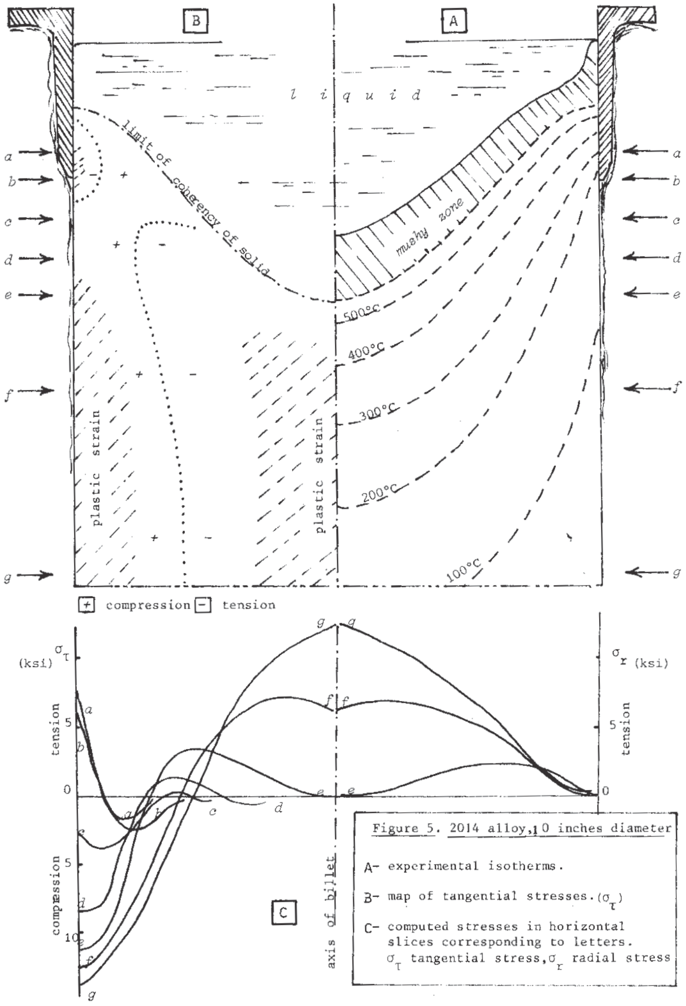


Figure 5. 2014 alloy, 10 inches diameter

A- experimental isotherms.

B- map of tangential stresses. (σ_T)

C- computed stresses in horizontal slices corresponding to letters. σ_T tangential stress, σ_r radial stress

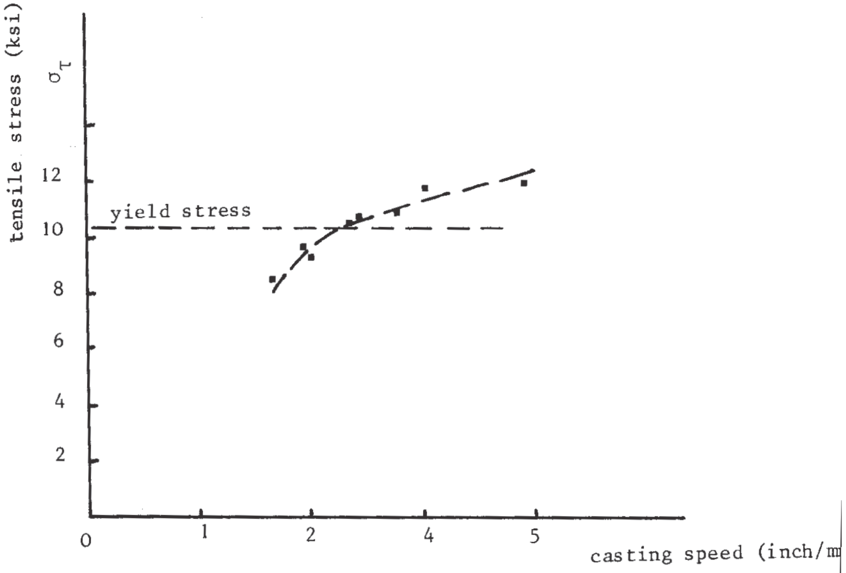


Figure 6. 2014 alloy, 10 inches diameter.

Influence of casting speed on tensile stress in the center of the billet after cooling.

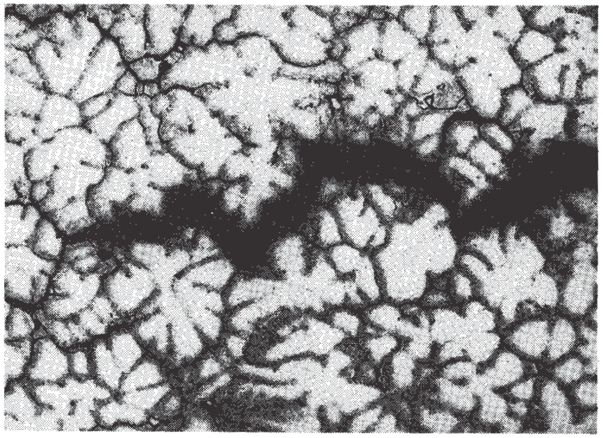


Figure 7 Microcrack or intergranular decohesion formed in the central part of 20 inches 7075 billet cast with low stresses. The cavity is refilled by eutectic at its extremity. x 60

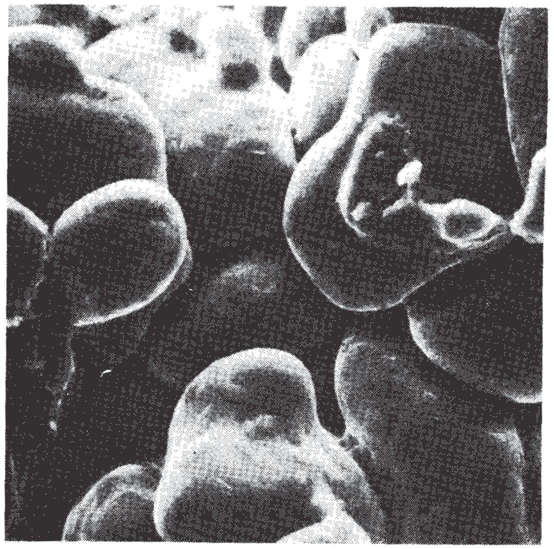


Figure 8 Surface of the microcrack. Electron scanning microscope. x 500